Acta Astronautica 118 (2016) 218–223

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

GEO objects spatial density and collision probability in the Earth-centered Earth-fixed (ECEF) coordinate system

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ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form
9 October 2015
Accepted 18 October 2015
Available online 28 October 2015

Keywords:
Space debris
Geostationary ring
Spatial density
Collision probability

ABSTRACT

The geostationary (GEO) ring is a valuable orbital region contaminated with an alarming number of space debris. Due to its particular orbital characters, the GEO objects spatial distribution is very susceptible to local longitude regions. Therefore the local longitude distribution of these objects in the Earth-centered Earth-fixed (ECEF) coordinate system is much more stable and useful in practical applications than it is in the J2000 inertial coordinate system. In previous studies of space debris environment models, the spatial density is calculated in the J2000 coordinate system, which makes it impossible to identify the spatial distribution in different local longitude regions. For GEO objects, this may bring potent inaccuracy. In order to describe the GEO objects spatial distribution in different local longitude regions, this paper introduced a new method which can provide the spatial density distribution in the ECEF coordinate system. Based on 2014/12/10 two line element (TLE) data provided by the US Space Surveillance Network, the spatial density of cataloged GEO objects are given in the ECEF coordinate system. Combined with the previous studies of "Cube" collision probability evaluation, the GEO region collision probability in the ECEF coordinate system is also given here. The examination reveals that GEO space debris distribution is not uniform by longitude; it is relatively centered about the geopotential wells. The method given in this paper is also suitable for smaller debris in the GEO region. Currently the longitudinal-dependent analysis is not represented in GEO debris models such as ORDEM or MASTER. Based our method the further version of space debris environment engineering model (SDEEM) developed by China will present a longitudinal independent GEO space debris environment description in the ECEF coordinate system.

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1. Introduction

The geostationary ring is a valuable orbital region contaminated with an increasing number of space debris. Due to its particular orbital character, the distribution of GEO objects is relatively susceptible to local longitude regions. This information must be considered when preparing to occupy a GEO longitude slot, and it is also critical to forecast the further evolvement of the GEO space debris environment [1].

In existing space debris environment models the spatial resolution is determined in inter coordinates J2000 [2–4]. Using various algorithms, the associated spatial density and collision possibilities are given then. Under such concept, longitude is distributed randomly between 0 and 2π. Mean longitude is widely used and spatial density in particular GEO geographic longitude slots cannot be determined. Therefore though average spatial density at GEO region may be

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http://dx.doi.org/10.1016/j.actaastro.2015.10.012
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estimated with such tools, local intersection events for certain geographic longitude slots are not accessible [5].

In order to overcome this disadvantage, the space debris spatial density in ECEF coordinate system is introduced in this paper, and the collision hazard is also discussed under the same concept. Therefore the spatial density and collision probability at each geographic longitude bin are clearly distinguished without using highly accurate analysis tools. It provides an effective and low-cost way to describe and forecast the GEO space debris environment. Although ECEF frame has been used in the investigations of near-miss events [6], it has not been used in the space debris environment models.

The US Space Surveillance Network (SSN) provides a catalog of earth orbiting objects. It nominally includes objects in Low Earth orbit (LEO) greater than 10 cm in diameter and lager than 1 m in GEO region. Based on 2014/12/10 TLE data [7], the spatial density of cataloged GEO objects are processed in the ECEF coordinate system. Combined with the previous studies of "Cube" collision probability evaluation [3,5], the GEO region collision rate in the ECEF coordinate system is also given in this paper.

The method is also suitable for smaller debris in the GEO region. Currently the longitudinal-dependent analysis is not available in GEO debris environment models such as ORDEM [8] or MASTER [9]. Based our research the further version of space debris environment engineering model SDEEM developed by China will present a longitudinal independent GEO space debris environment description in the ECEF coordinate system.

2. Brief characterization of the GEO objects

2.1. Definition of GEO

According to the Inter-Agency Space Debris Coordination Committee (IADC) space debris mitigation guidelines, the GEO protected region is defined as a segment of spherical space bound in altitude by 200 km below the GEO altitude (35,786 km, the altitude of the GEO earth orbit) to 200 km above the GEO altitude and in latitude by 15° on either side of the equator [10].

This paper mainly analysis cataloged objects on near circular orbits passing crossing the GEO region. The primary source of information is the U.S. Space Surveillance Network (SSN).

2.2. Orbital perturbation in GEO

Due to the non-spherical Earth gravity perturbation, in GEO region where the semimajor axis is about 6.6 times the earth radii, orbit objects are pulled towards two "geopotential wells" by the earth gravitational forces [11,12]. The centers of the geopotential wells are 75 E and 105 W. whether an object is trapped in geopotential wells or not depends on its original longitude and apogee/perigee relative to the GEO arc. There are four categories of GEO objects: trapped east, trapped west, trapped both and drifting. If the objects are trapped east or west, they will continuously oscillate about the center of the well for a long time. For the cases of drifting and trapped between, to complete one full cycle across a geopotential well takes about one to ten years, depending upon the range of the oscillation [1].

2.3. Current situation in GEO

Since 1963 when the first GEO satellite SynCom-2 was launched by America, there have been nearly four hundreds GEO satellites. Due to its orbital characteristics, GEO is a highly valuable orbital region with high traffic [13]. It has become the realm of the satellites mainly focus on communicating, navigation, global positioning, early warning, etc. Fig. 1 shows recent satellites orbits whose period is between 0.9 and 1.1 times of one sidereal day, eccentricity less than 0.2 and inclination less than 30°, which contains most of the objects passing through the GEO region. Fig. 2 shows the distribution of the longitude of these satellites, the longitude bin here is given as 3°. These satellites spend most of their time in the GEO region during their mission, highly affected by the GEO space debris environment.

Figs. 3–5 give the distribution of those objects in period, eccentricity and inclination. We can see that most GEO objects have period about a day, eccentricity less than 0.01, and inclination less than 20°.

Considered as one of the most noticeable space environments, orbital debris is a dangerous threat to all human space operations in present and future. It is also seen as a feedback of all kinds of space activities. Current space debris environment models have already considered the GEO region [9,14]. Therefore finding a better way to describe the GEO debris environment is necessary and meaningful for practical applications [6].

By the end of 2014, there were about 983 cataloged objects in the GEO region defined above. There are nearly 2200 objects with diameter between 30 cm and 1 m currently observed in GEO region, but failed to be cataloged. It is estimated that the number of objects larger than 10 cm would be more than three thousands [1]. The absence of earth atmosphere leads to the lack of natural forces, which cause the objects to decay. Therefore GEO objects' lifetime is more than thousands of years without de-orbiting activities.

Another unique characteristic about the GEO objects is that their longitude positions in the ECEF coordinate system is relatively stable in a couple of days, or even longer. That makes the collision possibilities between the GEO objects are relatively higher in some particular longitude regions,

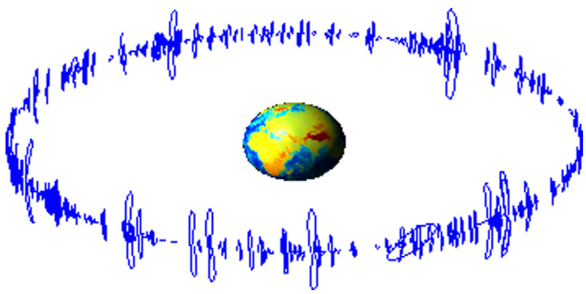

Fig. 1. Orbit tracks of GEO satellites in the ECEF coordinate system.

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